

Alcator C-MOD Lower Hybrid Project

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- ARIES studies show the remarkable improvement in the attractiveness of a tokamak reactor that could result from Advanced Tokamak physics operation and advanced technology.
- Key elements of AT operation assumed in ARIES-AT studies such as reversed shear with $q_{\min} > 2$, $H_H > 1$, $\beta_N \sim 3$ and $f_{BS} > 50\%$ have been demonstrated transiently in a number of tokamaks. However, such demonstrations have been limited to times less than a current redistribution time.
- By using lower hybrid current drive to supplement the bootstrap current, the potential of AT regimes can be developed and explored in Alcator C-MOD under quasi-steady-state conditions.
- The Lower Hybrid Fabrication Project provides for the installation of 3 MW of RF power at 4.6 GHz with 5 s pulse length in the C-MOD cell, together with an appropriate antenna to couple this power to C-MOD plasmas.

Alcator C-MOD is Well-Suited for AT Research

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- Internal PF coils provide strong shaping required to access high β_n and β_p (and therefore high bootstrap current) regimes.
 - Relatively small major radius means high net efficiency for current drive, I_{CD}/P .
 - Pulse length of 5 sec @ 5 T is comparable to the L/R time ($T \sim 5$ keV), an important time scale for reaching fully steady-state conditions. C-MOD is the only shaped tokamak presently with this capability.
 - The installed ICRH capability of 6 MW is sufficient to reach high β_n . Variable frequency antenna allows flexibility in power deposition profile and some control of pressure profile.

Lower Hybrid Current Drive is a Good Fit to Alcator C-MOD

- Lower hybrid has proven current drive capability. The current drive efficiency is highest of any current drive method.
- Current deposition profile is consistent with reversed shear scenarios, e.g., in ARIES-RS.
- Grill phasing permits dynamic control of $n_{||}$, which varies driven current deposition profile.
- Extensive experience with lower hybrid current drive systems at the PSFC, beginning with Alcator A, then Versator and Alcator C. PSFC experience is complemented by that of PPPL collaborators from PLT and PBX-M LH experiments.
- Reuse of equipment from the Alcator C LH experiment results in a highly cost effective fabrication.

Purpose: To develop and explore the potential of Advanced Tokamak regimes, i.e., regimes with high bootstrap fraction ($\sim 70\%$), high β_n (~ 3) and high confinement ($H_H \sim 1-2$) in Alcator C-MOD under quasi-steady-state conditions, $T_{\text{pulse}} \sim 5 \text{ s} \geq L/R$.

Tools: The main tools for these experiments will be a 4 MW Lower Hybrid RF system (New Fabrication) and 6 MW of ICRF heating (Existing System).

Ion Cyclotron Heating System

	<i>Phase 1</i> (Present Capability)		<i>Phase 2</i> (upgrade)
	Antenna 1&2	Antenna 3	Antenna 1&2
Frequency	80 MHz	40 – 80 MHz	40 – 80 MHz
Power	2 MW each	4 MW	4 MW each
Antenna	2 Straps	4 Straps	4 Straps

Lower Hybrid Current Drive System

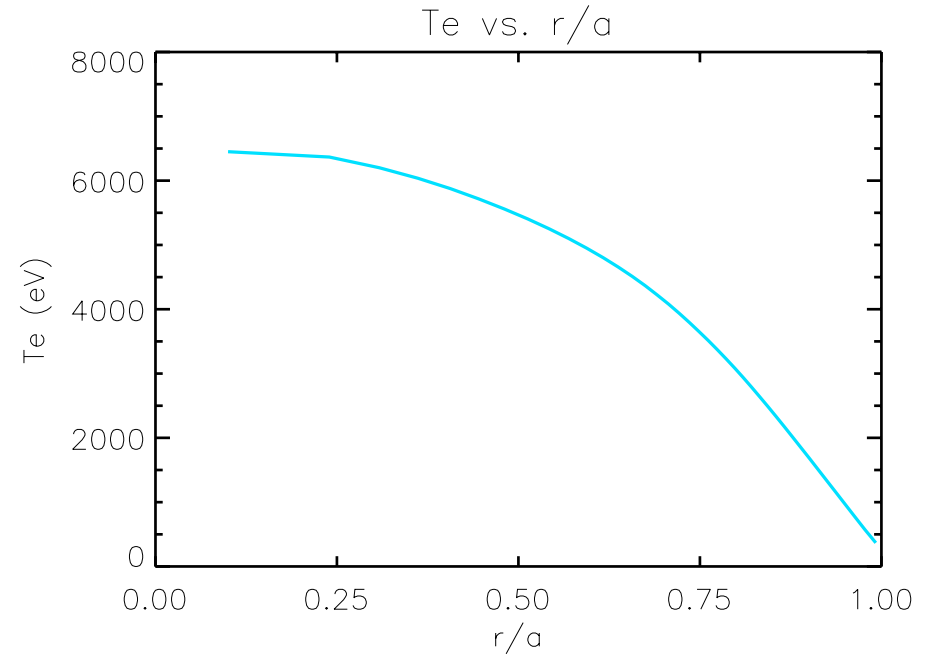
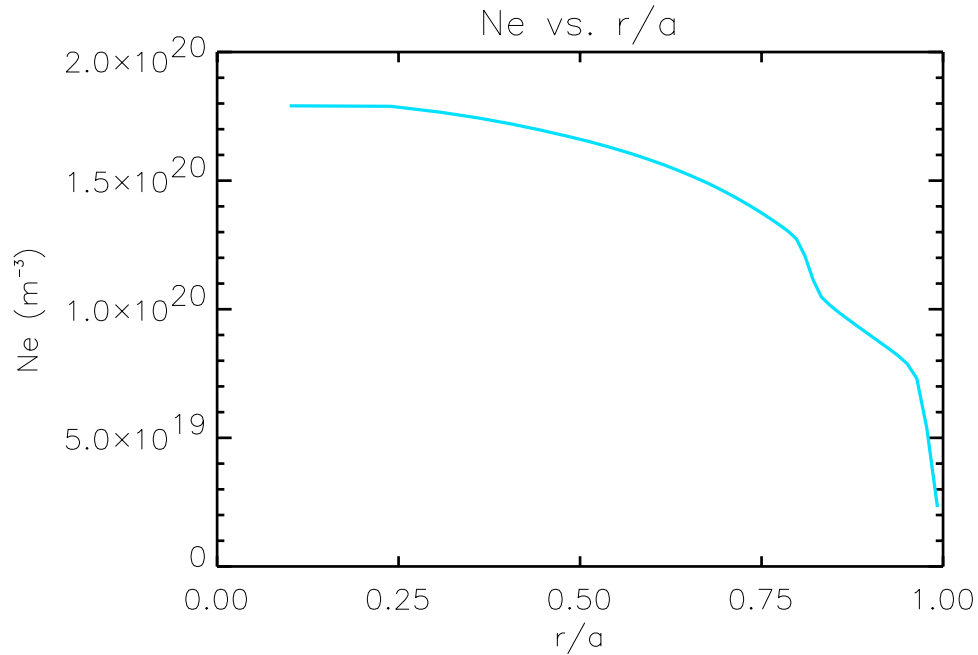
	<i>Phase 1</i>	<i>Phase 2</i>
Frequency	4.6 GHz	4.6 GHz
Power	3 MW	4 MW
Antenna	4X24 Waveguide Grill (1)	4X24 Waveguide Grills (2)
$N_{ }$ (Variable)	2-3	2-3

Modelling Studies Show the Basis for Steady State LH Driven AT Regimes in C-MOD

- Modeling studies by Bonoli, Ramos and Porkolab have established the basis for using LHCD to produce steady-state AT Regimes in Alcator C-MOD.
- The current density profiles developed in the modeling are in line with those assumed in the ARIES AT studies. However, a key issue is the stabilization of the $n = 1$ resistive wall mode. Without feedback stabilization, maximum $\beta_N < 3$. This is a generic tokamak issue!
- Somewhat serendipitously, a double transport barrier similar to that assumed in the density profile used in the modeling studies have been produced in C-MOD with off-axis ($R < R_{\text{mag}}$) ICRF heating.
- Although densities are somewhat higher than in the model, significant current drive is still possible with 2 MW of coupled lower hybrid power.

Plasma Profiles for Double Barrier Formation Near the β -limit

$$n_e(0) = 1.8 \times 10^{20} \text{ m}^{-3} \quad T_e(0) = 6.45 \text{ keV} \quad B_0 = 4.0 \text{ T}$$



$$p(\psi) = n(\psi)T(\psi)$$

$$T(\psi) = T(0)[0.7(1-\psi)^{3/2} + 0.3(1-\psi^4)]$$

$$n(\psi) = n(0)[(1-\psi) + \Delta n_I(\psi) + \Delta n_E(\psi)]$$

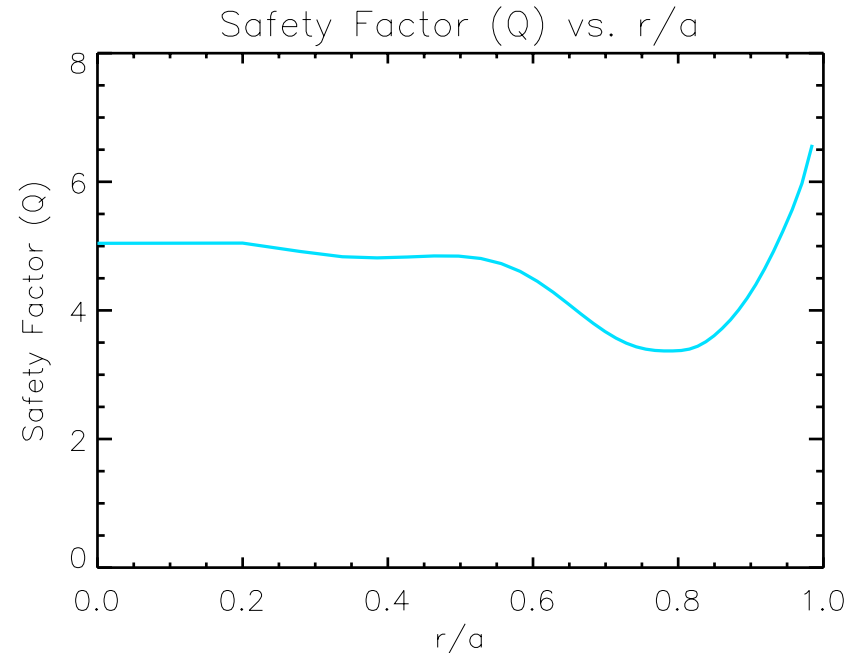
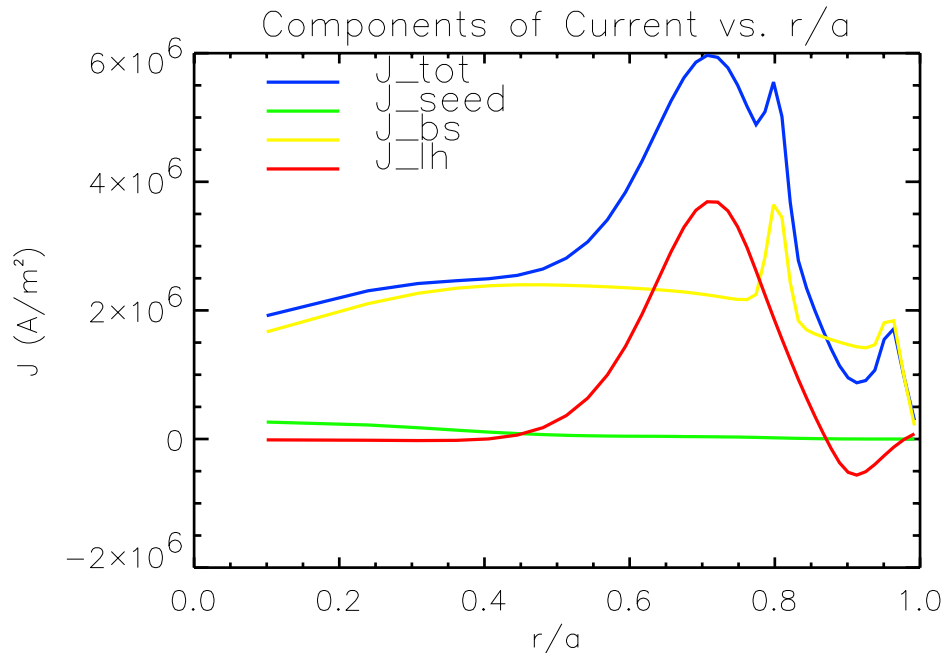
$$H_{\text{ITER-89}} \simeq 2.5$$

$$P_{\text{ICRF}} \simeq 5.0 \text{ MW}$$



Double Barrier Formation Near the β -limit ($B_0 = 4.0$ T, $\beta_N = 2.72$)

$$n_e(0) = 1.8 \times 10^{20} \text{ m}^{-3}, \quad T_e(0) = 6.45 \text{ keV}, \quad P_{\text{ICRF}} \simeq 5.0 \text{ MW}$$



$$I_p = 0.88 \text{ MA} \quad f_{\text{BS}} = 0.68$$

$$I_{\text{LH}} = 0.27 \text{ MA}$$

$$P_{\text{LH}} = 3.0 \text{ MW} \quad (n_{\parallel}^0 = 3.00)$$

Stable to $n = 1$ mode

Unstable to $n = \infty \rightarrow 0.88 \lesssim r/a \lesssim 0.94$

$$q_0 = 4.99 \quad q_{\text{min}} = 3.37$$

$$\beta_t = 2.60\%$$

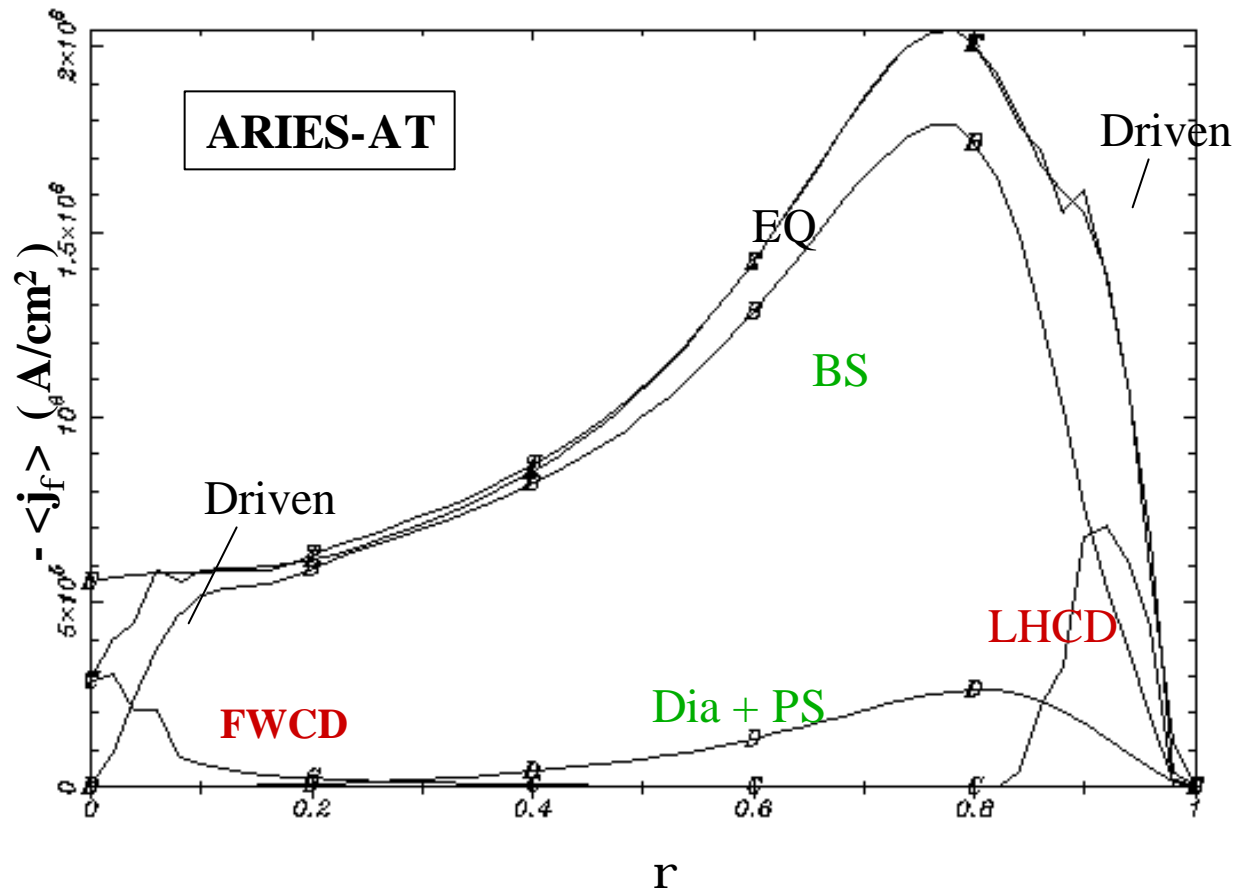
$$p(0)/\langle p \rangle = 2.15$$



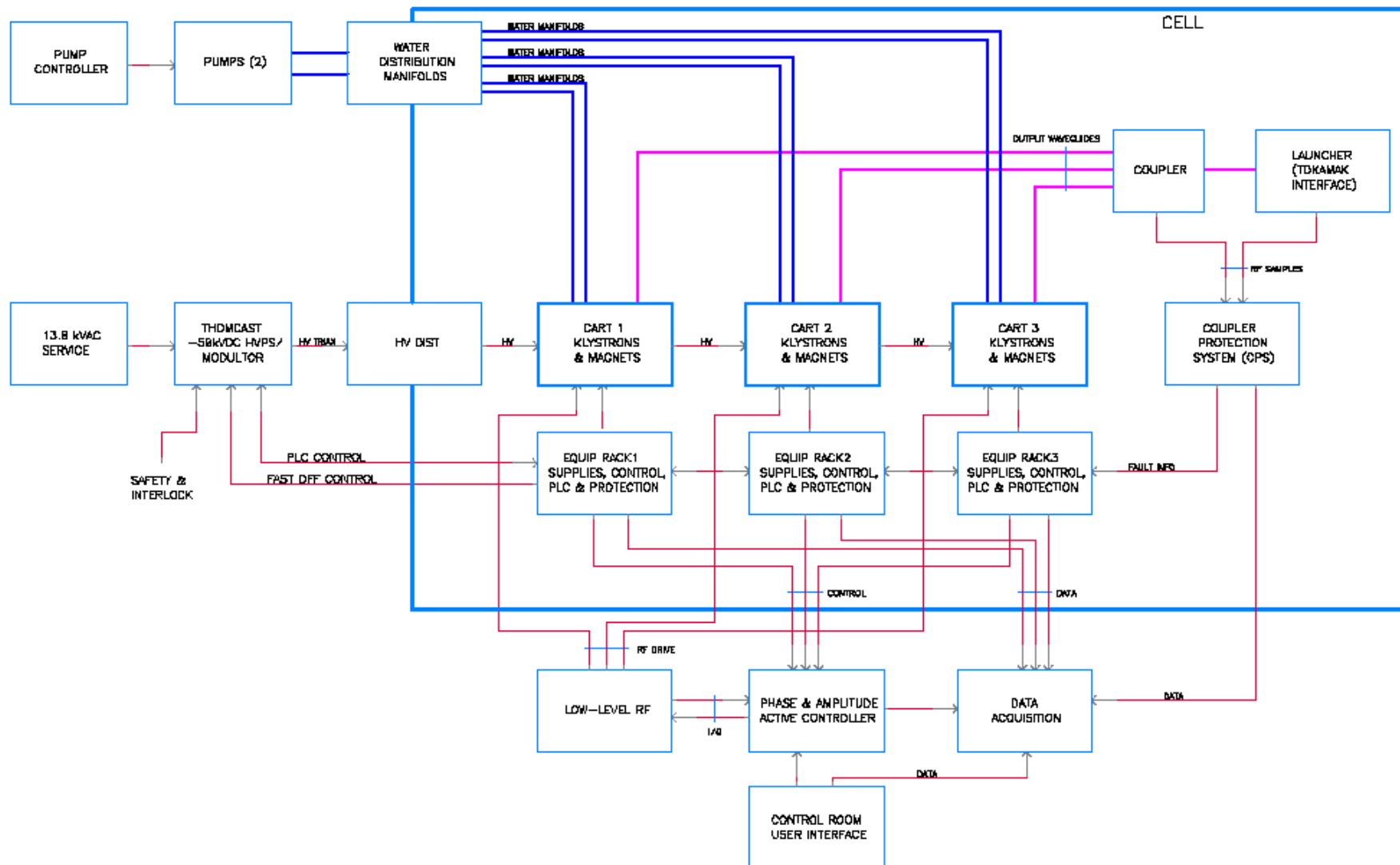
Target Equilibrium Can be Maintained with RF- and Self-Driven Currents

ARIES
PULSAR
STARLITE

- **2 RF schemes** are required to drive the seed currents on ARIES-AT:
(1) ICRF fast waves for on-axis drive; (2) LH waves for off-axis drive.



LOWER HYBRID BLOCK DIAGRAM

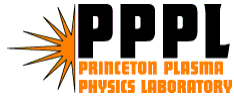




Excellent Progress Has Been Made During Past Year on RF System Design and Development



- The 16 klystrons returned to MIT after sojourns in PPPL and LLNL have been tested to ≥ 250 kW for 10 msec; 14 were found suitable for Phase I use (12 needed). The two remaining klystrons will require filament replacement.
- Three of the four carts supporting 4 klystrons each and used in Alcator C LH experiments have been refurbished and are nearly ready for installation in C-MOD cell.
- Contracts for the two large procurements, the power supply/modulator and isolators have been let. The vendors are well qualified and timely deliveries are expected.
- Design for a dynamic control amplitude and phase control system has been completed and the performance of a prototype is being evaluated.
- Development of a CPCI data acquisition system, which replaces CAMAC and which has broad application in the fusion community. Contract for 400 channel system with 1 Msample/channel (16 Bits) @ 250 kHz bandwidth has been placed.



PPPL is Has Also Made Excellent Progress on Coupler Design and R&D

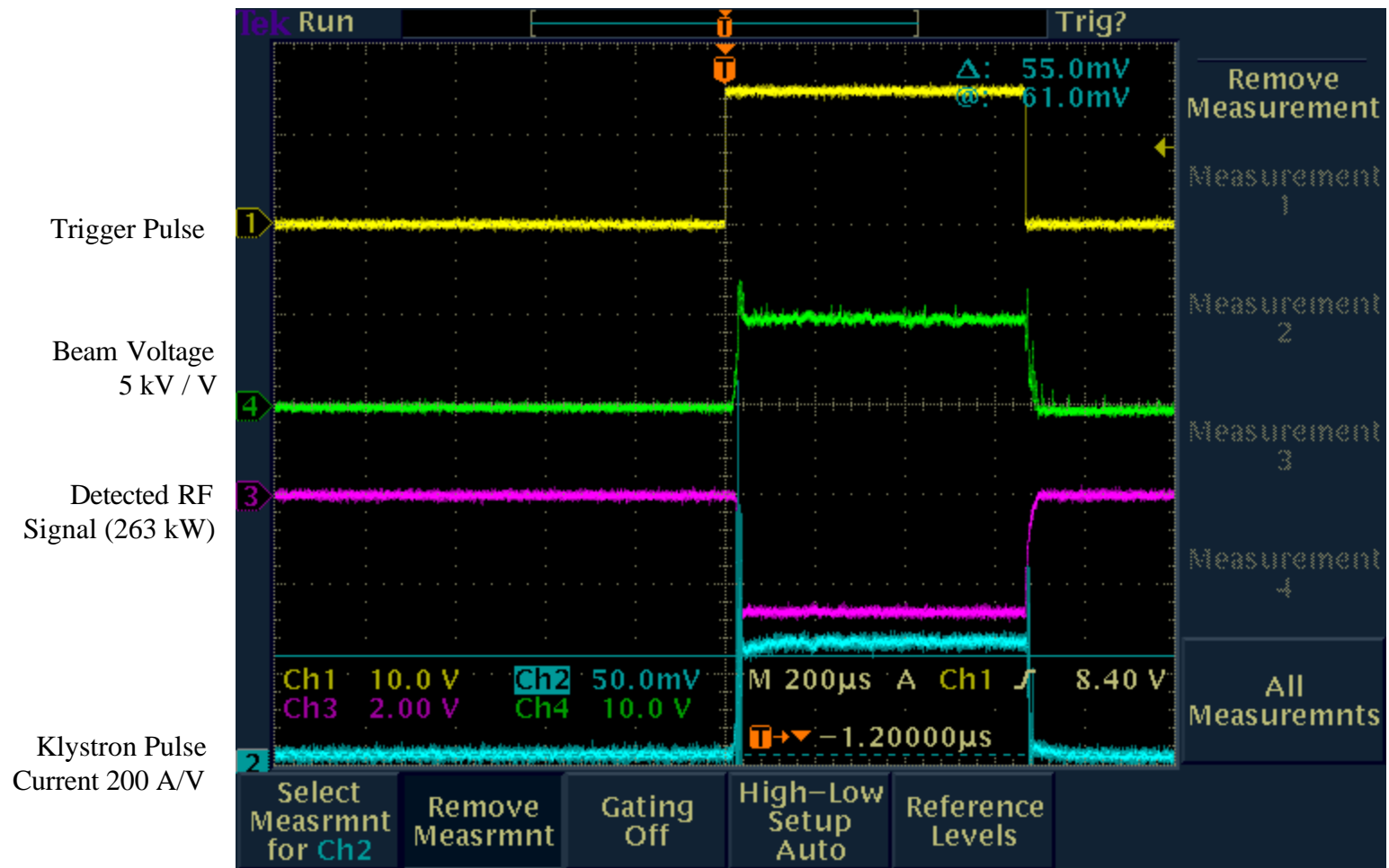


- Both Conceptual and Preliminary Design Reviews have been completed
- Two prototype 3-waveguide Couplers have been fabricated and are being used to:
 - Qualify machine shops for final manufacture
 - Investigate tolerance and flatness issues
 - Check coupler to stacked waveguide gasket fabrication
 - Evaluate Coupler losses and splitter performance
 - Evaluate taper to standard waveguide performance
 - Test and evaluate ceramic window brazing and performance

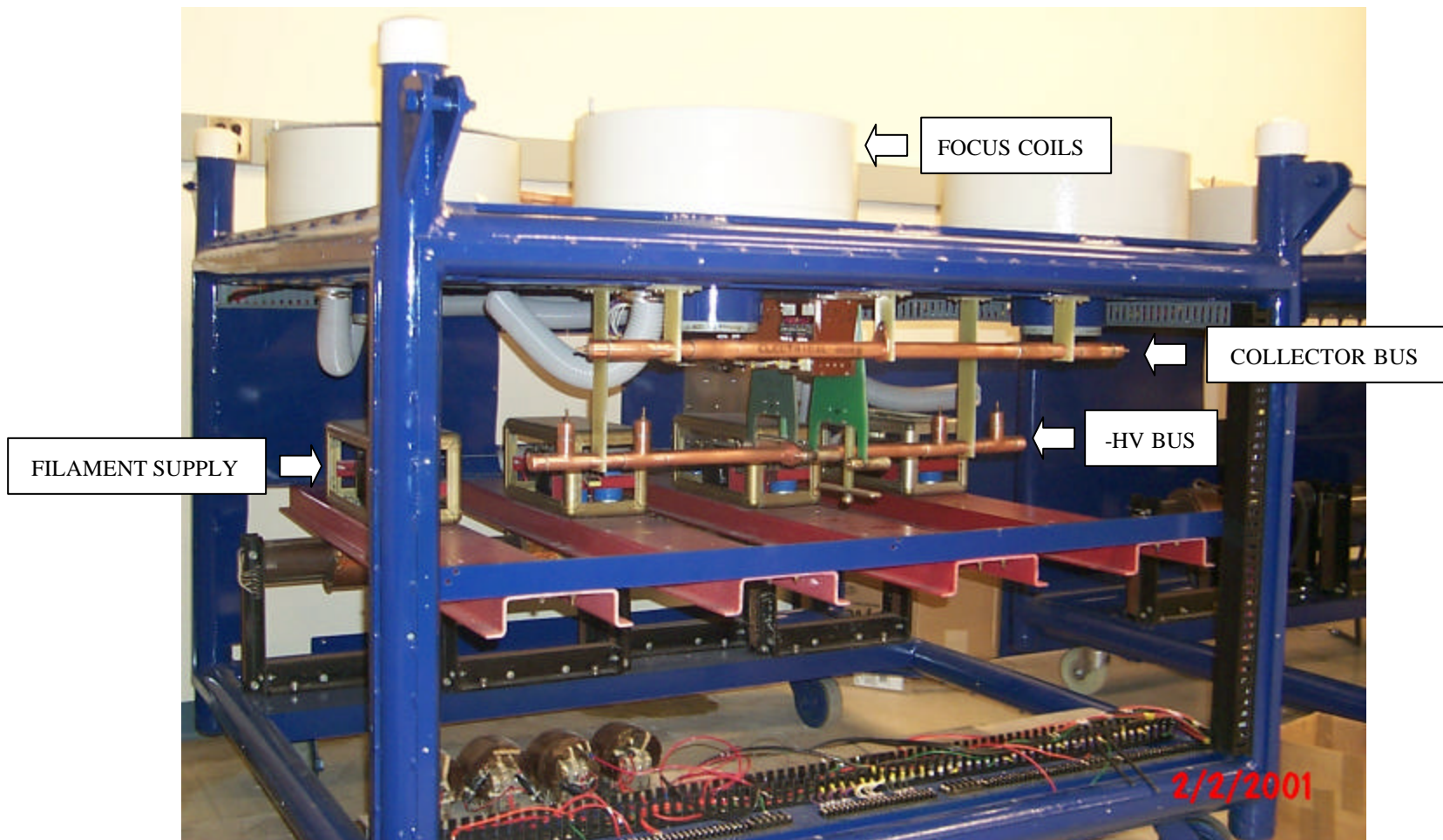
RF System - Klystrons



RF System – Klystron Test Data



RF System – Klystron Carts



High-Voltage Power Supply/Modulator

Key Specifications:

Output Voltage – 0 to -50 kV Regulated, Adjustable

Output Current – 0 to 208 A Adjustable Trip Point

Pulse Width – 5 Seconds

Duty Cycle – 0.5 % Max.

Flatness – $\pm 1/2$ %

Over/Undershoot – 2%

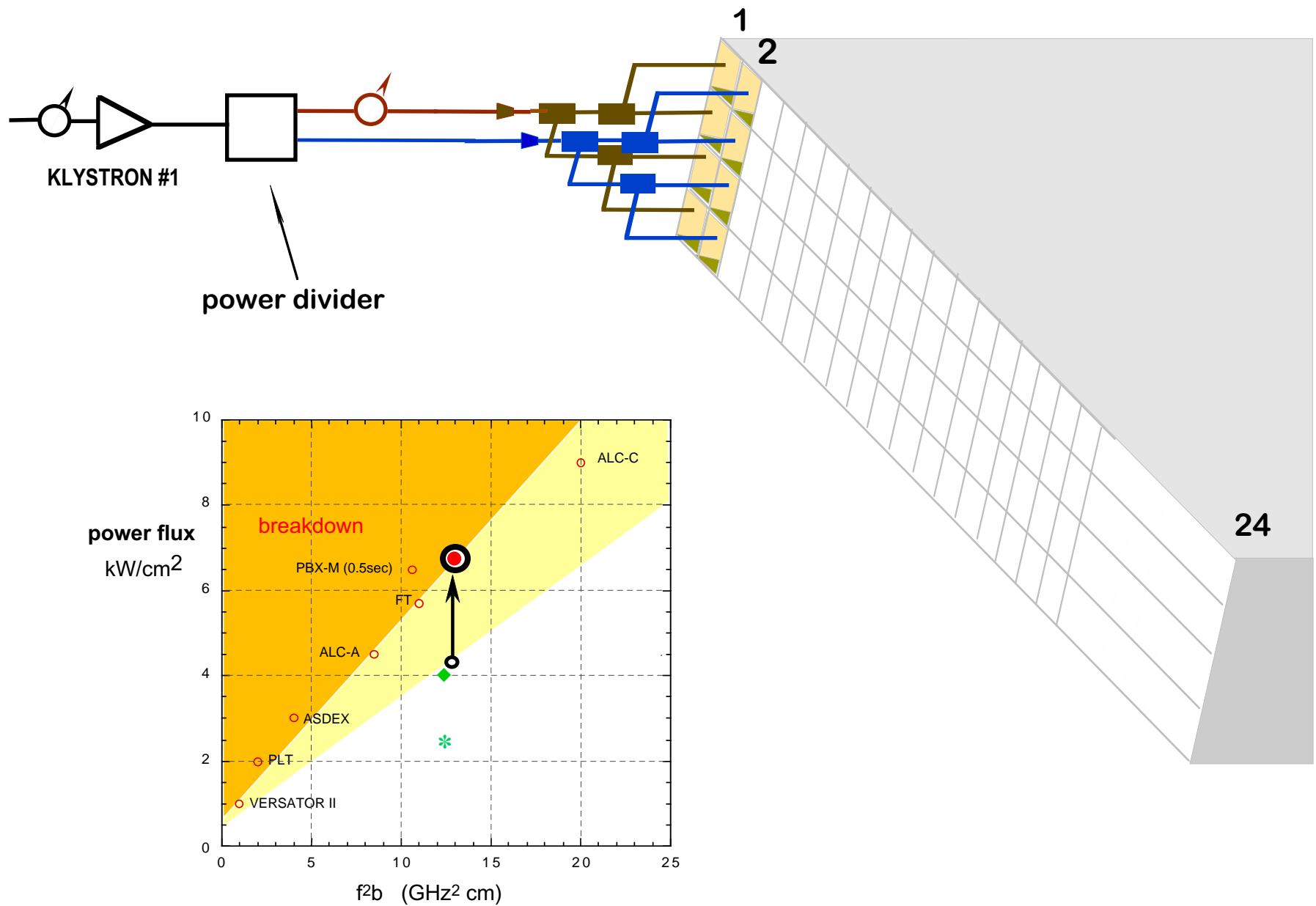
Rise/Fall Time – 50 μ s Adjustable, for Normal Operation

Fall Time for Fault – 3 μ s or Less

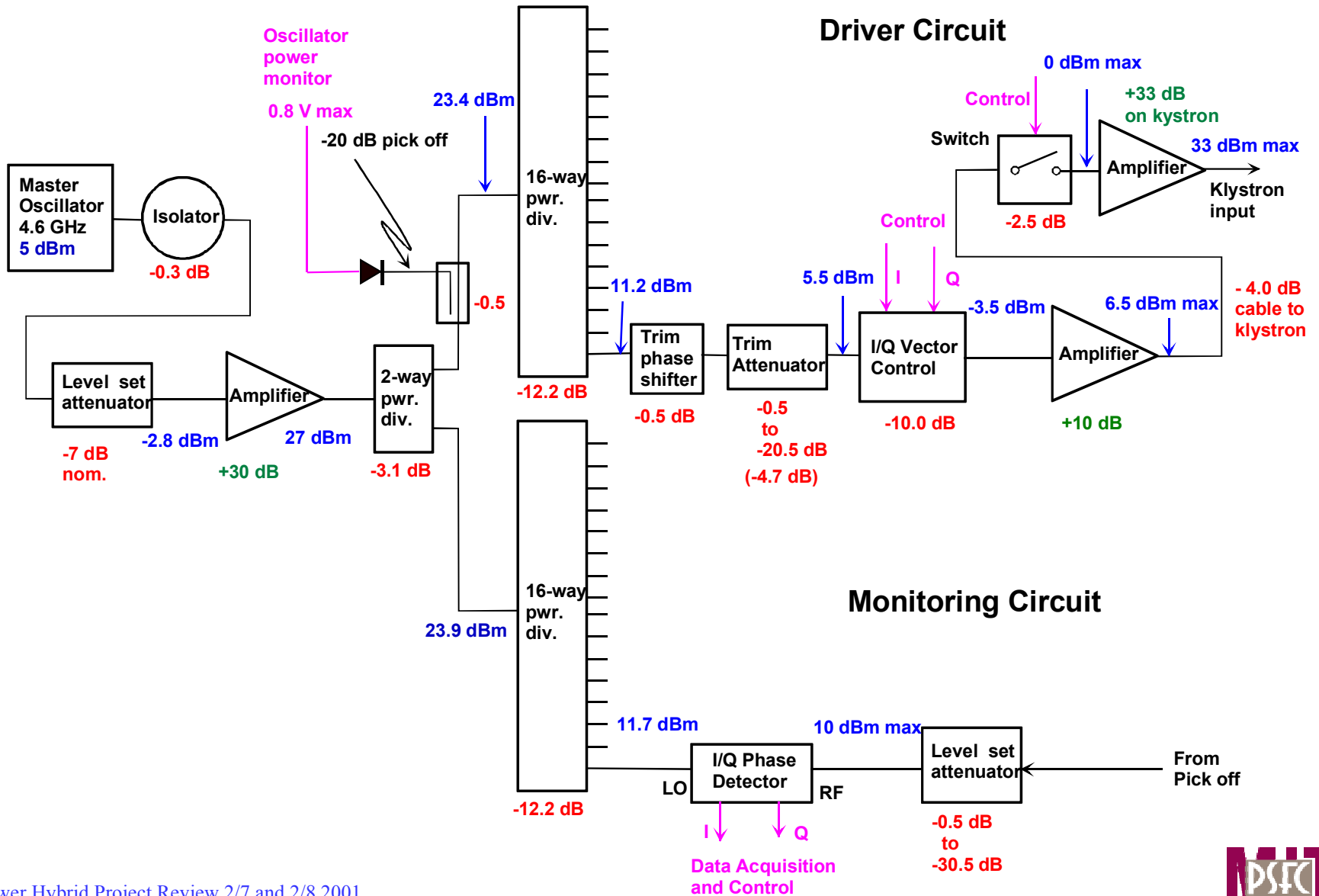
Line Voltage – 13.8 kV AC, 60 Hz, 3-phase

PLC Interface – Set Points and Status via Fiber-Optic Link

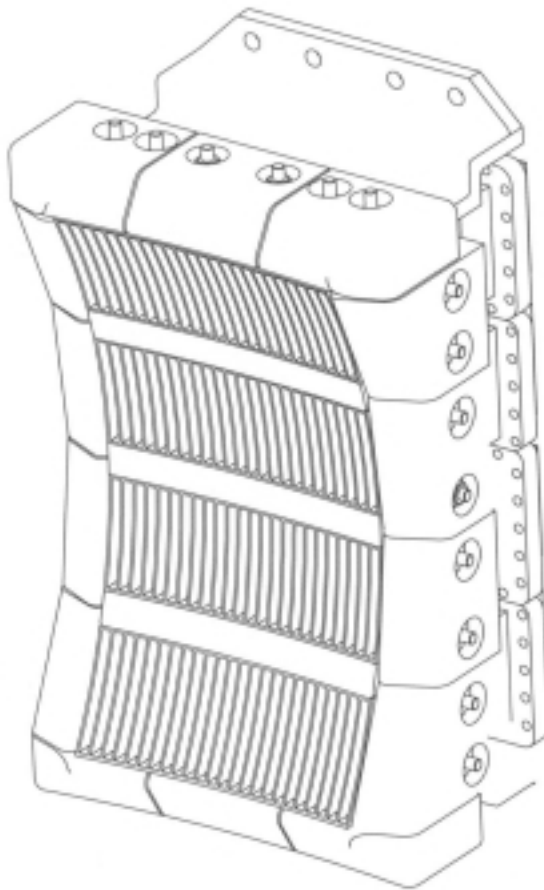
1st PHASE: 12 KLYSTRONS ON TO ONE COUPLER



Low Power LHCD Circuit Details



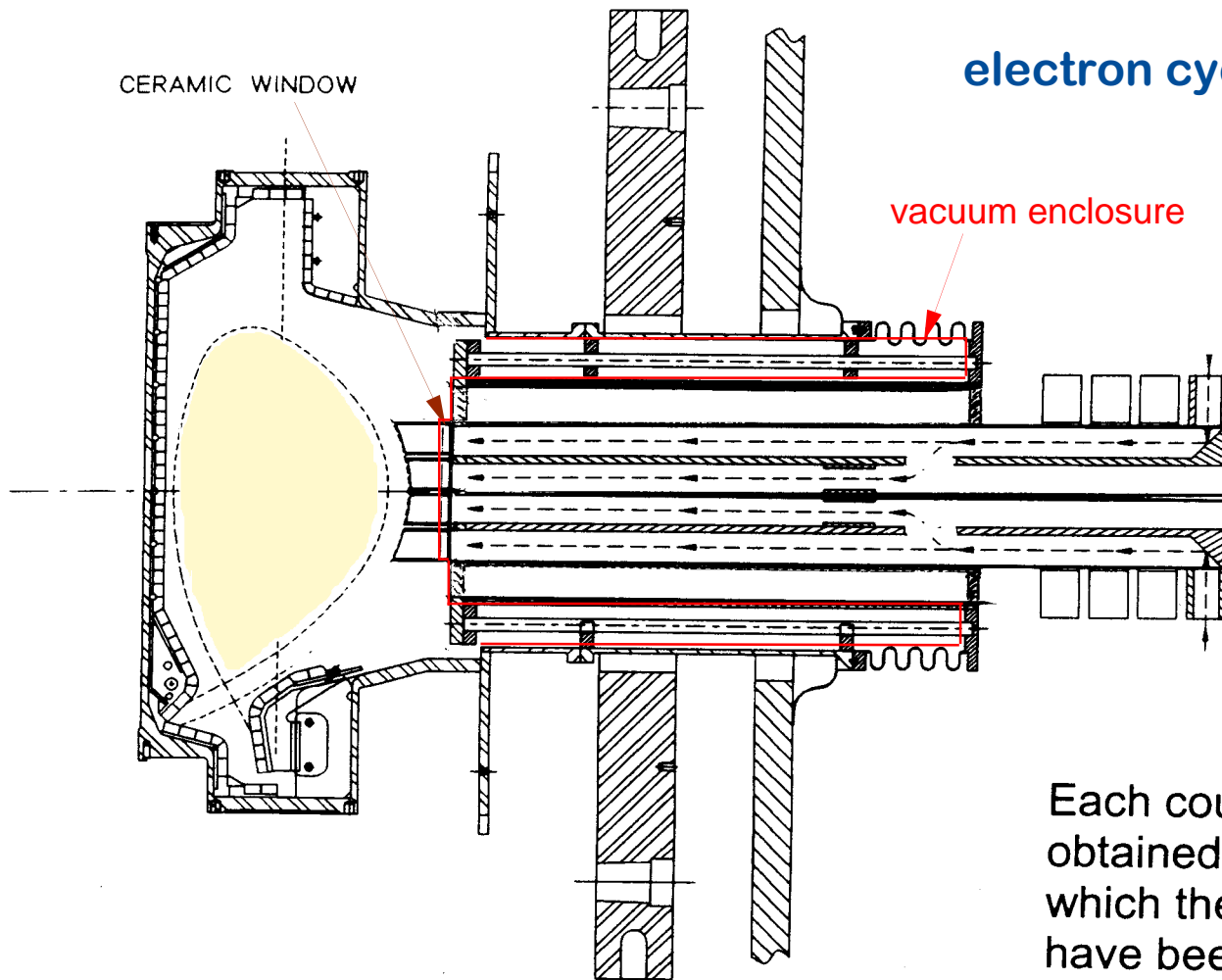
Coupler



- 24 waveguides X 4 modules
- Each channel waveguide vacuum sealed with Al_2O_3 ceramic brick
- Bricks will be coated and then brazed into the waveguide
- Module is then vacuum sealed to the rest of the launcher with a 0.03" gold seal
- TCs monitor temps

no waveguide joint in vacuum.

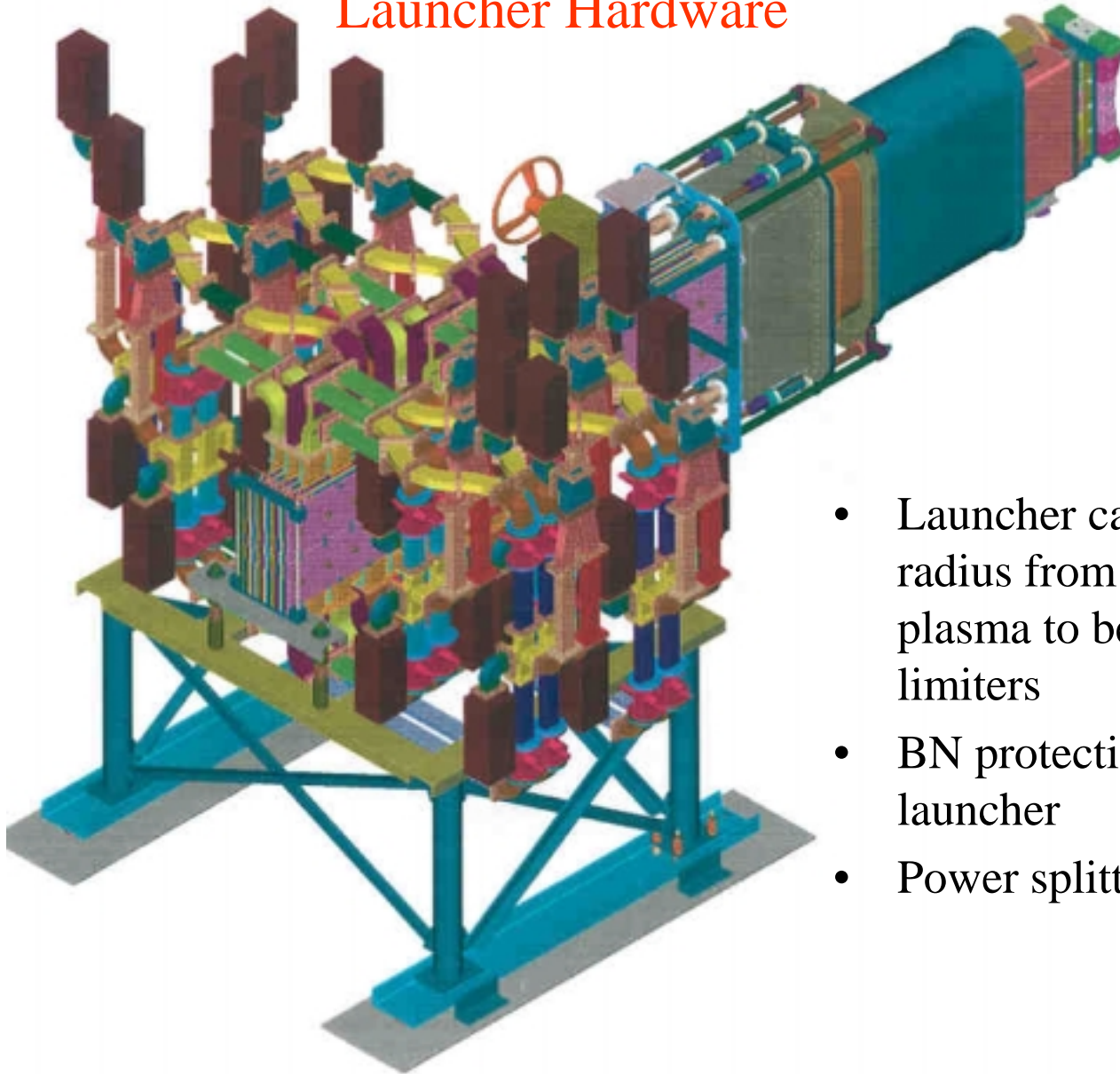
electron cyclotron layer in air side.



Each couple of adjacent arrays is obtained by stacking 24 plates on which the waveguides channels have been milled

SECTION ELEVATION
THRU MACHINE/ANTENNA

Launcher Hardware

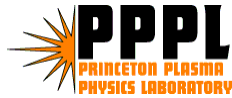


- Launcher can be moved in major radius from approx 0.5 cm from the plasma to behind other machine limiters
- BN protection tiles move with the launcher
- Power splitters built into launcher

- The project was approved in February 2000 with a completion target date of August 2002 (30 months) and an estimated cost of 4.2 M\$ without contingency.
- After completion of the pre-conceptual design last summer, the project baseline budget was established at 5.2 M\$ which remains the present projected cost. The funding profile is shown in the Table:

	<i>FY 00</i>	<i>FY 01</i>	<i>FY 02</i>	<i>FY 03</i>
Budget Profile				
PSFC	820	1350	730	400
PPPL	300	500	500	600
Total	1120	1850	1230	1000
Project Total	5200 (k\$)			

- The budget profile causes a delay in the original completion date. With the profile shown above, the completion date would be delayed 6 months beyond the original target date, with experiments beginning in March 2003. Moving FY 03 funds into FY02 would permit completion at the end of FY 02.



MIT is Making Substantial Contribution to the Lower Hybrid Project



MIT is providing the following:

- Cooling water system for klystrons, including piping, valves, pumps, etc.
- Mezzanine to support klystron carts in C-MOD cell
- Increased low voltage electrical capacity in cell
- Slab for High Voltage Power Supply in Alcator high voltage yard
- Run cabling from HVPS to C-MOD cell
- Run 13.8 service to HVPS
- New setup laboratories

Total value of MIT contributions is approximately \$1.5 M

Procurements for the RF Power System Are 80 % complete

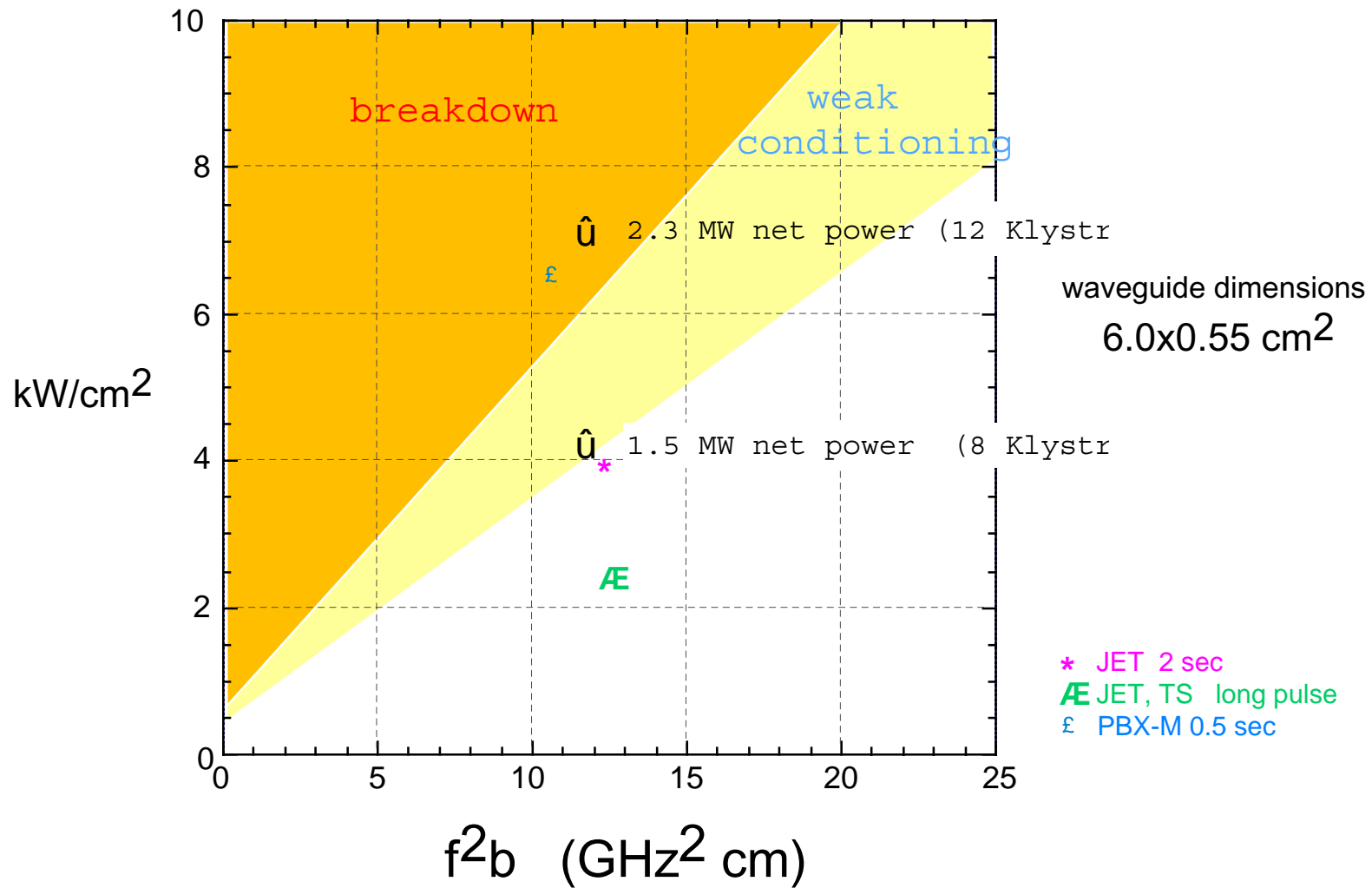
WBS	<i>Baseline Procurements</i>	<i>Committed to Date</i>	<i>Remaining</i>
2. AC-DC Power Conversion	1208	1208	
3. Klystron Cooling System	49 ¹		49
4. Low Level RF	90	7.6	82.4
5. Klystrons	138	123	15
6. RF Power Transmission	518	370	148
7. Instrumentation and Ctrl	480	272	108
Totals	2483	1981	402

¹MIT Contribution

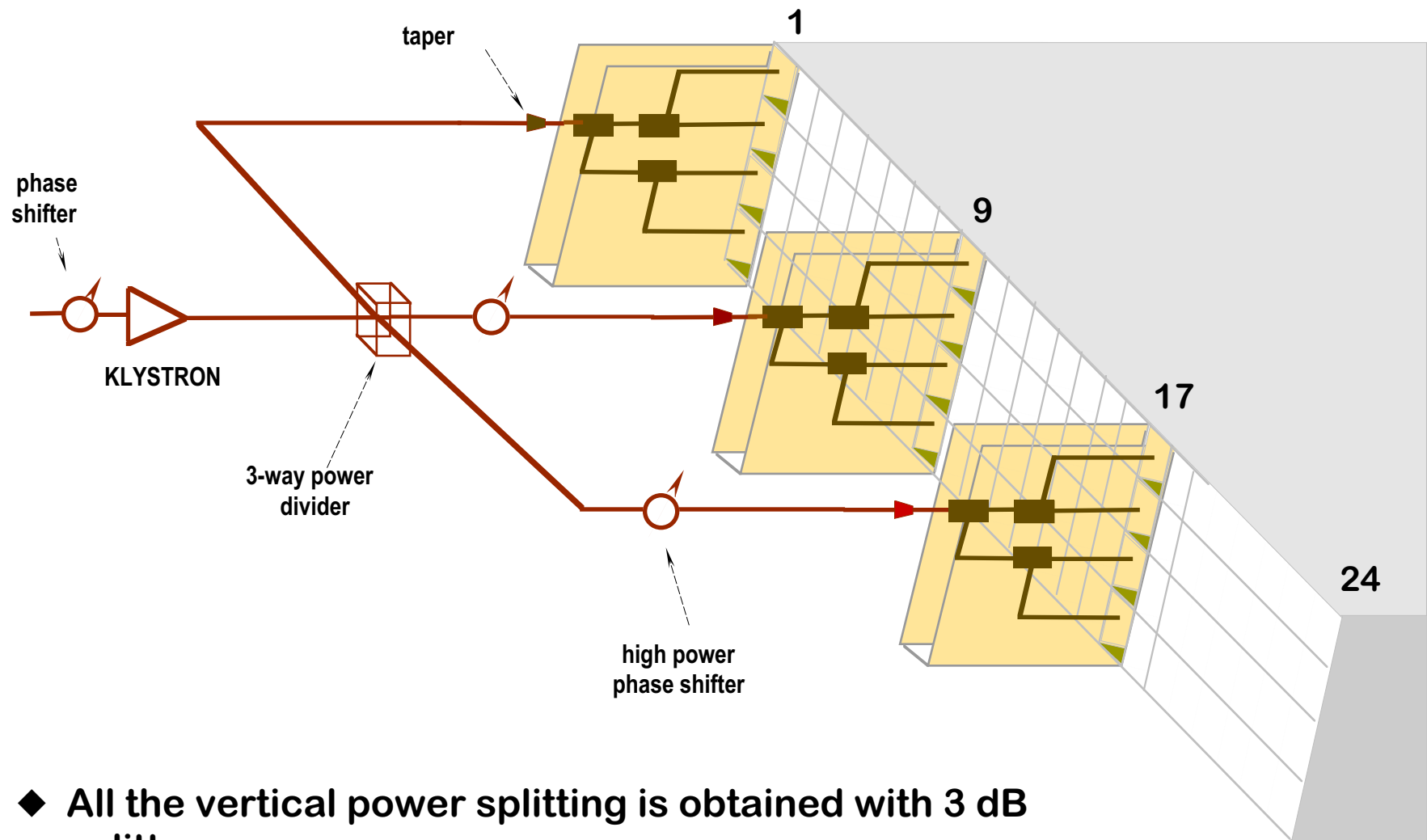
Upgrade of RF Power to 4MW Is Planned for FY 03 (Incremental)

- A main concern for the success of the lower hybrid experiments is the achievable power density. Empirical scaling suggests that coupling the full Phase I source power of 3 MW is optimistic.
- A Phase II is planned, which would add an additional MW but would also reduce the power density by adding an additional coupler.
- Initiation of the Phase II fabrication in FY 03 is foreseen in the incremental budgets of PSFC and PPPL.

power flux in the waveguides



COMPACT FEED DESIGN



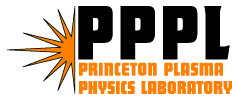
- ◆ All the vertical power splitting is obtained with 3 dB splitters.
- ◆ All the remaining transmission line is standard size.

Lower Hybrid Physics Studies Will Begin in FY 03

- FY 03 investigations will focus on coupler performance – optimizing RF match to C-MOD plasmas and determining current drive efficiency and ability to control profile.
- Key diagnostics are MSE measurement of total current profile and a new imaging X-Ray spectrometer for evaluating the distribution of lower hybrid driven current. The X-ray spectrometer is proposed to be designed and built in collaboration with Y. Peysson from Tore Supra.
- An important issue of high performance, high f_{BS} , regimes is the beta limit, which is expected to be due to the onset of resistive wall modes. Active MHD Spectroscopy system, now being installed for use in the next run campaign, will be used to determine both the proximity to RWM's and the feasibility of feedback stabilization.
- Should feedback stabilization show promise, planning for installation of control coils could occur in FY03.

Lower Hybrid Experiments on C-MOD Will Make Substantial Contribution to IPPA Goals

IPPA Top Level Goal	General Area of Contribution	In-depth Area of Contribution
3.1 MFE Goal 1: Advance understanding of plasma, the fourth state of matter, through well-diagnosed experiments, theory and simulation	3.1.1 Turbulence and Transport: Advance the scientific understanding of turbulent transport, forming the basis for a reliable predictive capability in externally controlled systems	3.1.1.2 Understanding Transport Barriers – explore roles of magnetic and velocity shear
	3.1.2 Macroscopic Stability: Develop detailed predictive capability for macroscopic stability including resistive and kinetic effects	3.1.2.1 Understanding Observed Macroscopic Stability Limits – use current profile control to understand limits to operation near β_n limit
	3.1.3 Wave-Particle Interaction: Develop fundamental understanding of plasma heating, flow, and current drive, as well as energetic particle instabilities,..., especially for reactor-relevant regimes.	3.1.3.1 Plasma heating and Current Drive – Check theory of current drive by lower hybrid waves, e.g., $f(\mathbf{v}, \mathbf{r})$. Investigate off-axis current drive and bootstrap current, and sustainment for $\sim L/R$ time scale.



Lower Hybrid Experiments on C-MOD Will Make Substantial Contribution to IPPA Goals



IPPA Top Level Goal	General Area of Contribution	In-depth Area of Contribution
3.3 MFE Goal 3: Advance understanding and innovation in high-performance plasmas, optimizing for projected power-plant requirements; and participate in a burning plasma experiment.	3.3.1 Profile Control: Assess profile control methods for efficient current sustainment and confinement enhancements, consistent with efficient divertor operation, for pulse length $\gg \tau_E$.	3.3.1.1 Plasma Current Profile: Develop consistent models of self (bootstrap) and LH driven current. Seek to demonstrate states of higher plasma density.
		3.3.1.2 Plasma Pressure Control: Explore use of variable frequency ICRF heating in conjunction with current profile control to improve plasma confinement and stability
	3.3.2 High β Stability and Disruption Mitigation: Develop and assess high- β instability feedback control methods and disruption control & amelioration in the AT, for $T_{\text{pulse}} \gg \tau_E$.	3.3.2.3 Active Profile Control to Avoid External Boundaries: Use active control of current and pressure profiles to maintain profiles stable to known operational boundaries.